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Gravitational Microlensing of Giant Luminous Arcs: a Test for Compact Dark Matter in Clusters of Galaxies

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Abstract: The true nature of dark matter in the universe still eludes us. This paper discusses a new test for the detection of stellar mass compact dark matter in galaxy clusters by observing its gravitational lensing influence on the surface brightness of giant luminous arcs. If dark matter is in the form of stellar mass compact objects, then the extremes of such variability are accessible to a monitoring campaign with the Hubble Space Telescope. With the advent of the Next Generation Space Telescope, cluster dark matter in the form of compact objects will induce a ubiquitous 'shimmering' of the giant arcs.

Keywords: galaxies: clusters: general — gravitational lensing — dark matter

1 Introduction

After several decades of dedicated searching, the nature of cosmological dark matter still eludes us. The two main contenders have been neutrinos and massive compact objects, although recent results suggest that neutrinos are not massive enough to be cosmologically important (Fukuda et al. 1998). Large microlensing surveys have also cast doubt on the importance of compact objects, demonstrating that they are not a significant contributor to the mass budget of the Galactic halo, with only a few tens of percent of the mass of the Galactic halo in the form of compact objects (e.g. Lasserre et al. 2000). This conclusion, however, is uncertain as the dark matter in the Galactic halo may be quite lumpy (e.g. Klypin et al. 1999), with our view towards the Magellanic Clouds unfortunately representative of an under-dense line-of-sight, and hence microlensing experiments to date may not have measured the true overall density of compact objects within the halo.

As clusters of galaxies represent the largest bound concentrations of matter in the universe, their density of dark matter makes them ideal laboratories to probe its nature. Walker & Ireland (1995) proposed that compact dark matter could be detected via its gravitational microlensing influence on our view of distant quasars observed through clusters of galaxies, as this would introduce a flickering into their light curves. Tadros, Warren, & Hewett (1998) undertook such a search, monitoring ~ 600 quasars behind the Virgo cluster. The vicinity of the Virgo cluster, however, makes it a very poor gravitational lens, with the optical depth in compact objects being ~ 0.001, so any microlensing induced variability would be rare. Moving to more distant clusters can greatly 'improve' the lensing geometry, significantly enhancing the microlensing optical depth, although the number of quasars expected behind such distant clusters falls rapidly. Compensating this, a moderate to large number of clusters must be investigated to ensure a significant population of quasars for study. All of this is further exacerbated by the need to untangle microlensing variability from the intrinsic variability displayed by the majority of quasars.

2 Giant Arcs

Given the difficulty of detecting compact cluster dark matter using quasars, we must search for other objects behind clusters that would be useful sources. Obvious candidates are the giant luminous arcs and associated arclets, as they offer several immediate advantages over quasars. Firstly, the giant arcs are a product of strong lensing and so the gravitational lensing geometry for such systems is more favourable than for nearby clusters, such as Virgo. Also, giant luminous arcs are common in distant clusters, with many such examples known (Fort & Mellier 1994). Finally, whereas a quasar provides a single view through a cluster, the giant luminous arcs are quite extended, some covering several tens of square arcseconds, offering many lines of sight. On the face of it, however, their large, extended nature appears to act against using giant arcs as microlensed sources, as sources must be smaller than the Einstein radius of a microlensing mass, of the order of a microarcsecond at cosmological distances, to produce significant magnification (e.g. Wambsganss 2001). On closer examination, however, the apparently smooth light in the arcs is actually composed of small discrete sources, namely stars.

In understanding how microlensing affects the stars in the giant luminous arcs, we can make a simple comparison to gravitational microlensing within the Local Group. Figure 1 presents a schematic representation of three regimes of microlensing. In the upper panel, a single source is microlensed by an isolated compact object; this situation describes the low optical depth microlensing in the Galactic halo and of quasars seen through nearby clusters, and results in a simple bell-shaped light curve (Paczyński 1986). The magnification of the source can be

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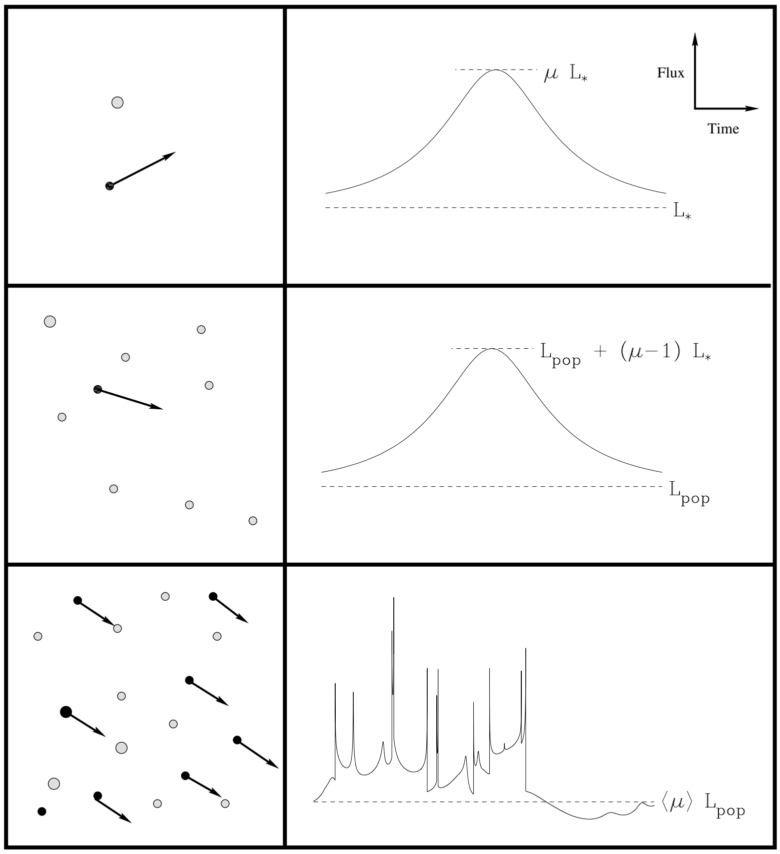

Figure 1 Three regimes of microlensing. The left hand panels present the projected MACHO (black dot) positions in front of the stellar sources (grey dots), the arrows denoting the motion of the MACHOs. From the top to the bottom we have the low optical depth case towards the low projected density of stars. This is the case for the Magellanic Clouds where single stars are microlensed. The corresponding right hand panel shows the light curve of this event, where the apparent luminosity of the star (L_*) is magnified by a factor μ, resulting in a characteristic bell-shaped light curve. The central panel represents a low density of MACHOs towards a high stellar surface density; this corresponds to microlensing towards M31. Individual stars are unresolved, and the image of the source region registers the light from a population of stars, L_{pop}. The MACHO enhances the apparent luminosity of a single star in the population, again resulting in a simple bell-shaped light curve, but this is seen against the luminosity of the total population, as illustrated in the right hand panel. The lower panel presents the situation discussed in this paper, where a high optical depth of MACHOs lies in front of a dense stellar population. In this case, a large fraction of source stars will be significantly magnified at any instant. The resulting light curve is quite complex, with many rapid changes on short time scale, as depicted in the right hand panel. The large optical depth implies that the source undergoes significant macrolensing and the variations are with respect to the theoretically expected mean magnification, $\langle\mu\rangle$.

large, although the rarity of such events makes detection difficult. Large monitoring programs, such as MACHO (Alcock et al. 2000), have been successful in their hunt for microlensing, with several hundred microlensing events towards the Galactic bulge and about twenty towards the Magellanic Clouds over the last decade. The central panel of Figure 1 represents microlensing towards M31, where individual source stars can no longer be resolved. Here pixels in an image register the sum of an underlying population of stars. As a compact object moves in front of this population, it will occasionally magnify one of the stars in the source population. While the observed flux from this star can be significantly enhanced, it is seen relative to the unresolved background of stars, and it is only the microlensing of the brighter stars in a population that results in a significant deviation in the brightness of a pixel. Coupled with the fact that our view towards M31 presents a small optical depth, such 'pixel lensing' (Crotts 1992) events are relatively rare. The lower panel of Figure 1 presents the case we are considering in this paper, namely gravitational microlensing of the stars in the giant luminous arcs. As with M31, the flux in a single image pixel corresponds to the light from a population of stars. Unlike the Local Group, however, the optical depth towards the luminous arcs is roughly unity, meaning that there will be a large population of microlensing objects in front of the stellar population. At any instant, therefore, a large fraction of the stars will be substantially magnified. The brightness of the region will be seen to fluctuate about a mean magnification which is determined by the large scale gravitational lensing properties of the cluster (see Lewis, Ibata, & Wyithe 2000 for more details). Due to the high optical depth, the magnification due to the stars consists of a complex web of regions of high magnification (see Wambsganss 2001) resulting in an equally complex light curve.

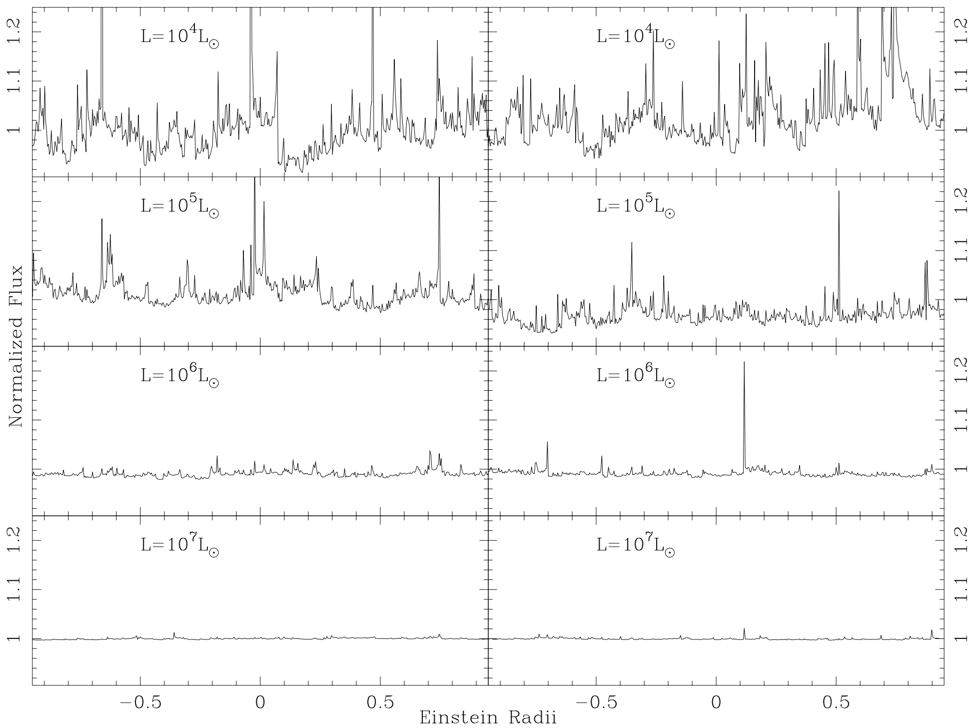

Figure 2 The left and right panels are two realisations of the expected variability of the surface brightness of the giant luminous arcs. From top to bottom, the total luminosity of the source population is increased from $10^4 L_\odot$ to $10^7 L_\odot$ (see Lewis et al. 2000).

Microlensing simulations were undertaken to determine the characteristics of the variability. For this, a single location through the giant arc in Abell 370 was chosen as a fiducial model, with an optical depth of $\sigma = 0.6$ and shear of $\gamma = 0.2$. For these parameters, a large catalogue of microlensing light curves was generated using the efficient contour-following algorithm of Lewis et al. (1993). The pixel scale of the light curves was chosen such that the maximum magnification of a light curve (due to the finite size of the pixel) was $\sim$300; this naturally corresponds to the maximum magnification of giant stars at cosmological distances, the dominant stars in terms of their contribution to the luminosity of a stellar population. In this study it has been assumed that all cluster dark matter is in the form of compact objects. If MACHOs only represent a fraction of the dark matter, as suggested by recent microlensing surveys of the Galactic Halo, then the microlensing optical depth is correspondingly lowered. This changes the characteristics of the microlensing light curves, with ‘events’ becoming rarer. The work presented here, therefore, represents the more extreme case. It should be noted, however, that as the macrolensing optical depths through clusters are roughly unity in the vicinity of the giant arcs, a MACHO mass fraction of $\sim$10% will still result in substantial variability. Any observed variability, therefore, would provide a limit on the true mass density of MACHO objects.

As the brightness of a pixel in an image is related to the luminosity of the stellar population it encompasses, four populations of stars were considered, with total luminosities per pixel of 10^4, 10^5, 10^6, & $10^7 L_\odot$. The simulation method involved drawing individual stars from a luminosity function and multiplying them with a randomly selected light curve, to produce a microlensed view of that star. Stars are drawn until the total luminosity of the population is accounted for, then all the light curves are summed to provide a microlensed view of the entire population. Figure 2 presents several examples of these light curves; it is immediately apparent that these possess variability on a range of time scales. Also apparent is the fact that as the luminosity of the underlying population is increased, the degree of variability falls; in the lower luminosity populations, moderately luminous stars that are lensed can induce a large fractional change to the brightness of a pixel. In higher luminosity populations, the same microlensed star induces less of a fractional deviation. In the highest luminosity population considered, only small variations are seen, due to microlensing of the most luminous stars.

In considering the degree of this microlensing induced variability, Lewis, Ibata, & Wyithe (2000) demonstrated that a dedicated monitoring campaign with the Hubble Space Telescope of the giant arc in Abell 370 could reveal $\sim$8 extreme events per 1000 pixels with the comparison of images from two epochs, with 10^4 sec exposures. The view with the Next Generation Space Telescope will greatly improve the situation, with the higher resolution and depth uncovering variability over 25% of the arc between epochs.

3 Ongoing Work

The work presented in Lewis, Ibata, & Wyithe (2000) considered only a single fiducial model when modelling the microlensing influence on the giant arc in Abell 370. While this is sufficient for demonstrating the expected degree of microlensing induced fluctuations, what is required to undertake an observational search for microlensing in clusters of galaxies is a map of the expected signature over the arcs. To this end we are currently using the high resolution mass and shear maps of Abell 2218 and Abell 370, derived from a gravitational lens analysis of HST images (see Kneib et al. 1996), which provide the macro-lensing parameters over the giant arcs. Combining these with extensive catalogues of the microlensing magnification probability distributions (Lewis & Irwin 1995), detailed predictions of the expected surface brightness variability across the giant arcs will be made.

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